REVIEW OF THE PROBABILISTIC SEISMIC HAZARD ANALYSES FOR THE PADUCAH GASEOUS DIFFUSION PLANT—FINAL REPORT

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1 INTRODUCTION

The 1992 Energy Policy Act (EPAct), passed as an amendment to the 1954 Atomic Energy Act, gives the Nuclear Regulatory Commission (NRC) the authority to establish and enforce regulations for safety and safeguards at the Paducah Gaseous Diffusion Plant (PGDP), which is operated by the United States Enrichment Corporation (USEC). Because the U.S. Department of Energy (DOE) was the pre-EPAct operator of the PGDP, the EPAct also incorporated a provision that allowed the USEC to utilize the DOE Compliance Plan (Toelle, 1997) to bring the facility into compliance with NRC regulations. Included in the compliance plan is a commitment by the DOE to perform a probabilistic seismic hazard analysis (PSHA) and submit the analysis to the NRC for review and comment. In September 1998, the USEC submitted to the NRC an updated PSHA report for the PGDP (Risk Engineering, Inc., 1998a). In addition to this PSHA report, the USEC provided responses to NRC requests for additional information (RAIs) to complement the PSHA report (Risk Engineering, Inc., 1998b, 1999; Toelle, 1998). Review of the PGDP PSHA was based on information furnished in the updated PSHA report, responses to the RAIs, and selected documents referenced therein. The review has drawn upon other sources of information such as U.S. Geological Survey (USGS) regional and site-specific data, Center for Earthquake Research and Information (CERI) data, and published studies in the general geological, geophysical, and seismological literature. The review also included checking consistency of the PGDP PSHA with relevant DOE standards (U.S. Department of Energy, 1994a,b); however, the Center for Nuclear Waste Regulatory Analyses (CNWRA) reviewers acceptance criteria did not rely on DOE standards.

The objective of this review was to ensure the applicant has adequately performed a PSHA of earthquake-induced ground shaking at the PGDP based on consideration of available regional and site-specific data in order to estimate the peak ground acceleration (PGA) for a seismic event with a 250-yr return period, or if the estimate is greater than 0.15g, the estimate of the return period for a 0.15g event. The adequacy of the USEC PSHA was evaluated with regard to applicable NRC regulations (Nuclear Regulatory Commission, 1998a,b,c) and regulatory guidance documents (Nuclear Regulatory Commission, 1973, 1997a,b). This review evaluated the resolution of three overall issues related to the PSHA for the PGDP: (i) whether all significant concerns related to defining the seismic hazard and free-field surface ground motions at the PGDP are addressed, (ii) whether the results are consistent with the overall approaches defined in NRC regulations and DOE standards, and (iii) whether any limitations regarding use of the results for the PGDP have been identified.

The following outlines the areas addressed in Chapter 3, Conduct of Review, of this report.

- Seismic Source Characterization
    - Geologic and Tectonic Setting
    - Historical Seismic Record
    - Correlation of Earthquake Activity with Geologic Structures or Tectonic Provinces
    - Maximum Earthquake Potential
- Earthquake Recurrence Characteristics
    - Seismic Activity
    - Clustered Earthquakes
    - Recurrence–Magnitude Models
- Ground-Motion Estimates
    - Attenuation Functions for Rock
    - Site-Response Models
    - Uncertainties

Hazard Calculation and Presentation

- Structure of the PSHA
- Uncertainties
- PSHA Calculation
- Hazard Results

The review is presented following a summary of the regulatory requirements. Evaluation findings are summarized in chapter 4 of this report. Although several uncertainties remain regarding source characterization and ground-motion attenuation (see section 4), the Risk Engineering, Inc. (REI) (1999) report satisfies established NRC requirements and accepted provisions of the DOE Compliance Plan.

2 REGULATORY REQUIREMENTS

The applicable NRC regulation governing licensing of Gaseous Diffusion Plants is 10 CFR Part 76 (Nuclear Regulatory Commission, 1998a). Because this regulation does not directly specify the methods to be used for seismic hazard analyses, relevant NRC regulations and guidance documents prepared for other nuclear facilities were used in this review. Additional NRC regulations include 10 CFR Part 50 (Nuclear Regulatory Commission, 1998b) and 10 CFR Part 100 (Nuclear Regulatory Commission, 1998c). The primary NRC guidance document used to conduct this review is the final PGDP PSHA review plan (RP) (Chen et al., 1998). Other NRC guidance documents applicable to this review include (i) recommendations for PSHA by the Senior Seismic Hazard Analysis Committee (SSHAC) (1997), (ii) Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a), (iii) NUREG–0800: Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants (Nuclear Regulatory Commission, 1997b), and (iv) Regulatory Guide 1.60 (Nuclear Regulatory Commission, 1973).

The principal difference between existing NRC regulations and associated RPs and the RP for the PGDP PSHA pertains to the reference set of earthquake and ground-motion standards. Because existing NRC regulations (Nuclear Regulatory Commission, 1998b,c) were drafted for nuclear power plants, they rely on the determination of two design-critical levels of vibratory ground motion. These ground-motion values are based on characterization of the Safe Shutdown Earthquake as defined in appendix A (III) of 10 CFR 100.23 (Nuclear Regulatory Commission, 1998c). In contrast, the Compliance Plan calls for the PGDP PSHA to explicitly define the PGA for the anticipated seismic event with a 250-yr return period. If that level of ground motion exceeds 0.15g, then the return period of the 0.15g event must also be estimated. The PGDP PSHA RP (Chen et al., 1998) accounts for these differences between existing NRC regulations and the special provisions in the Compliance Plan.

Pertinent sections of NRC regulatory requirements (Nuclear Regulatory Commission, 1998a,b,c) include 10 CFR 76.35(a)(4), 76.35(e), 76.85, and 76.87; 10 CFR 50.34 and appendix A, Criterion 2; and 10 CFR 100.23 and appendices A(I), (IV), (V), and (VI).

Pertinent sections of NUREG–0800 (Nuclear Regulatory Commission, 1997b) include Sections 2.5.1 (Basic Geologic and Seismic Information) and 2.5.2 (Vibratory Ground Motion).

3 CONDUCT OF REVIEW

The CNWRA reviewers conducted a technical review of the adequacy of the PSHA performed by REI for the PGDP (Risk Engineering, Inc., 1998a). The review focused on identification of significant safety issues. The reviewers examined the REI report to determine whether the acceptance criteria detailed in the RP (Chen et al., 1998) are met. Areas that needed additional information to support the review were identified as RAIs and transmitted to REI (Pierson, 1998a). The transmission of RAIs was followed by detailed discussion of various technical aspects of these RAIs between the review staff and relevant USEC and REI personnel at the REI offices in Boulder, Colorado during May 18–19, 1997 (Persinko, 1998). The meeting at the REI offices also included review of quality assurance applied to the analysis. Several deficiencies were identified. Based on discussions at this meeting, REI revised its seismic report and provided a written response to the RAIs (Risk Engineering, Inc., 1998b). The CNWRA reviewers further reviewed the REI responses and the revised report and generated the second and third rounds of RAIs (Pierson, 1998b; Galloway, 1999). The responses to the second and third round RAIs (Toelle, 1998; Risk Engineering, Inc., 1998b, 1999) were considered adequate to complete the technical review.

Besides the PSHA report submitted by REI, additional information obtained from the visit at the REI offices in Boulder, Colorado, and technical discussions, the CNWRA reviewers also reviewed relevant information in the open literature, regional and site-specific data published by the USGS, CERI, and other investigators. The reviewers evaluation included the acceptability of various technical aspects of the PGDP PSHA, including seismic source characterization, earthquake recurrence characteristics, ground-motion attenuation functions, and calculation and presentation of the seismic ground-motion hazard. These aspects were evaluated against acceptance criteria described in the RP (Chen et al., 1998). Detailed evaluation of these aspects is discussed in the following sections. Evaluation findings are summarized in chapter 4 of this report.

3.1 SEISMIC SOURCE CHARACTERIZATION

Potential sources of seismicity that affect the determination of the peak ground motion for the 250-yr return period and the estimation of the return period for the 0.15g event have been adequately characterized in REI (1999). Determination of the seismic sources included (i) characterization of the geologic and tectonic setting of the site and region, (ii) enumeration of regional earthquakes in the available historic seismic record, (iii) evaluation of capable faults in the region including correlation of earthquake activity with geologic structures or tectonic provinces, and (iv) estimation of the maximum earthquakes and maximum vibratory ground motion anticipated at the site. Each of these facets of the seismic source characterization are described in detail in the following sections. As noted in REI (1999) and in the RP (Chen et al., 1998), the PGDP lies within the New Madrid Seismic Zone (NMSZ), which is geographically east of the 105° west longitude cutoff for Central and Eastern United States sites. However, following NRC Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a), evaluation of the seismic hazard at the PGDP followed procedures normally applied to the Western United States.

3.1.1 Geologic and Tectonic Setting

Findings of the REI (1999) report with regard to geologic and tectonic settings relied on a summary report by Dr. Arch Johnston (Center for Earthquake Research and Information, University of Memphis, Memphis, Tennessee) and Dr. R. VanArsdale, (Department of Geological Sciences, University of Memphis, Memphis, Tennessee). That summary is provided as appendix A of the REI (1999) report.

The PGDP sits between two tectonic zones with differing seismicity: the NMSZ and the Wabash Valley Seismic Zone (WVSZ) (Risk Engineering, Inc., 1999). The NMSZ is located south of the PGDP and is part of the larger Mississippi Embayment. Seismicity generated within the NMSZ, including the three large earthquakes of 1811 and 1812, is considered to originate along reactivated faults of the underlying Phanerozoic Rift System, relic Iapetan rift structures formed during the breakup of the Neoproterozoic supercontinent Pannotia (e.g., Dalziel, 1997). Most notable of these structures is the Reelfoot Rift. The WVSZ lies under and north of the PGDP and includes the Rough Creek and Grayville grabens. The Rough Creek graben is also considered a relic Neoproterozoic rift feature, and connects the Reelfoot Rift with the Rome Trough farther east.

The nature of the Grayville Graben is less certain. Competing interpretations suggest it formed in response to Paleozoic growth of the Illinois basin (Bear et al., 1997) or as a failed third arm of the Neoproterozoic rift system (Braile et al., 1982; Marshak and Paulsen, 1997). The distinction is important to the PGDP seismic investigation because of possible linked faulting and seismicity between the NMSZ and WVSZ. In the former interpretation, the NMSZ and WVSZ were never linked structurally. In the latter interpretation, seismicity in southern Illinois may be potentially linked to the NMSZ because of motion along the Commerce Fault segment, which is proposed to form the western border fault of the Reelfoot Rift (Langenheim and Hildenbrand, 1997).

Alternatively, the Grayville Graben may have been structurally connected to the Reelfoot Rift in the Paleozoic. Uplift of the Pascola Arch in the late Paleozoic or Mesozoic, however, structurally isolated the WVSZ from the NMSZ (Cox and VanArsdale, 1997). Because there is an abrupt change in the character of seismicity between the two zones, findings of REI (1999) treat the WVSZ and NMSZ as discrete seismic zones. In support of their treatment, they cite the lack of a well-developed rift structure north of the Rough Creek Graben and a change in the pattern of seismicity between the two zones. There are relatively frequent earthquakes that can be directly associated with faults in the NMSZ compared to infrequent and diffuse seismicity in the WVSZ.

The style of deformation of the NMSZ is well known because of recent and historic earthquakes (Russ, 1982; VanArsdale, 1997). Focal plane solutions from historic earthquakes, reflection seismic data, and occasional surface ruptures define a northeast-trending right lateral strike-slip zone with a compressional (left-stepping) restraining bend [see figure A-18 in appendix A of REI (1999)]. This sense of motion is consistent with the contemporary stress field (Zoback et al., 1992). The style of deformation of the WVSZ is less certain. Right-lateral strike-slip appears to dominate with minor normal faulting. To date, no Holocene (last 10,000 yr) faulting has been identified (Nelson et al., 1997). Quaternary faulting is mapped in two areas, but historical earthquakes cannot be tied directly to these structures.

The nature of the East Prairie Fault or faults, especially their lengths, are not well constrained (Risk Engineering, Inc., 1999). Based on recent historical seismicity and an assumption that the fault produced the 1895 Charleston, Missouri, moment magnitude (**M**) 6.6 earthquake, Johnston (1996) estimated a total fault length of 65 km. However, magnitude-length scaling relationships seem to require a fault at least 100 km long to account for the 1812 **M** 7.8 earthquake. The fault is parallel along strike with mapped faults in the Fluorspar fault complex (Nelson et al., 1997), but no direct connection between the two sets of structures has been mapped. Assuming the East Prairie faults extend to the Fluorspar faults yields a total length of 160 km. Both 100- and 160-km alternatives were incorporated into the PGDP seismic hazard analyses.

Pursuant to NRC guidance and criteria (1995, 1997a,b, 1998a,b,c), this section of the PGDP study (Risk Engineering, Inc., 1999) is acceptable because adequate information was provided to demonstrate that a thorough investigation of the local and regional tectonic setting was performed. The investigation of geologic and tectonic setting was of sufficient scope such that all potentially significant seismic sources related to the New Madrid region (including, but not limited to the Reelfoot Rift, Rough Creek Graben, Upper Mississippi Embayment, southern Illinois Basin) were identified and assessed. The characterization of the tectonic setting and identification of capable seismic sources were based on regional and site geological and geophysical data, historical and instrumental seismicity data, regional stress field data, and geological investigations of prehistoric earthquakes, all derived from numerous published papers and reports [see appendix D of the NRC Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a)]. Bases for the identification of potential capable seismic sources (both fault and area sources) were documented.

Questions critical to seismicity at the PGDP concerning the possible interactive nature of the Reelfoot Rift and Rough Creek Graben, the northern extent of the East Prairie Fault zone, and the seismic potential of the Wabash Valley fault zone were addressed and incorporated into the hazard assessment. As described in section 2.5.2.2 of NUREG–0800 (Nuclear Regulatory Commission, 1997b), information used to determine the tectonic setting of the PGDP was developed into a coherent, well-documented discussion that was used to assess the seismic potential of the site. Specifically, this discussion provided the basis for

- Determination of the earthquake potential of identified geologic structures
- Determination of the earthquake potential tectonic zones (i.e., regions of uniform earthquake potential)
- Evaluation of uncertainties associated with seismic source geometry (e.g., fault dip, width, segmentation, depth of seismogenic crust)
- Evaluation of uncertainties in recurrence and recurrence models (section 2.2 of this review report) with regard to individual faults, clustered fault activity, or regional recurrence models

In addition, the report provided appropriate alternatives that allowed incorporation of epistemic uncertainties about the geology and tectonic conditions into the estimate of seismic hazard.

Following section 2.5.2.2 of NUREG–0800 (Nuclear Regulatory Commission, 1997b), the most important factors concerning evolution and setting of the region since the Pliocene (e.g., neotectonic) and pattern and level of historical seismicity were presented. Regional tectonic models derived from the geological literature or previous Safety Analysis Reports and NRC Safety Evaluation Reports were also discussed. The discussion was augmented by reliable geological maps and cross-sections drawn at appropriate scales of observation that showed all relevant tectonic provinces, tectonic features, capable faults, and historical earthquakes. These maps and the accompanying report included results of investigations required by 10 CFR 100.23 (Nuclear Regulatory Commission, 1998c).

3.1.2 Historical Seismic Record

Findings of the REI (1999) report with regard to the historical seismic record used an earthquake catalog compiled by Mueller et al. (1997), which was based on earlier national catalogs of Seeber and Armbruster (1991) and the Electric Power Research Institute (EPRI) (1988). The catalog was modified to remove duplicate events and all magnitudes were converted to **M** using the methods of Johnston (1996) and

Hanks and Kanamori (1979). Earthquakes with magnitudes larger than **M** 5.5 in the Paducah region were checked for consistency against the listing of Johnston et al. (1993) and corrected accordingly. A summary is provided as appendix B of the REI (1999) report.

Pursuant to NRC guidance and criteria (1995, 1997a,b, 1998b,c), this section of the PGDP study is acceptable because an adequate catalog of historical earthquakes was provided, including pertinent geological and seismological parameters associated with each event. The catalog included all earthquakes with Modified Mercalli Intensity values greater than or equal to IV or **M** ≥ 3.0 that have been reported in any of the identified tectonic provinces (see section 3.1.1 of this review report) or within 200 mi of the site following section 2.5.2.1 of NUREG–0800 (Nuclear Regulatory Commission, 1997b). Specifically, the catalog enumerated all relevant parameters including coordinates of the epicenter, focus depth, time of event, highest intensity, magnitude (converted to **M**), seismic moment, distance to the site, surface rupture information (when available), and appropriate references.

Reliable earthquake maps drawn at appropriate scales of observation showing the locations of earthquakes, including one showing the detailed seismicity within 50 mi of the site, were presented [see figures 3-2, A-1, A-2, A-9, A-11, and A-22 of REI (1999)].

3.1.3 Correlation of Earthquake Activity with Geologic Structures or Tectonic Provinces

Findings of REI (1999) identified nineteen potential fault sources and four potential areal sources (or generalized seismic source zones) that could contribute to the seismic hazard at the PGDP [see table A-1 in appendix A of Risk Engineering, Inc. (1999)]. Fault sources were differentiated hierarchically on the basis of (i) known historical seismicity, (ii) Holocene (last 10,000 yr) offset, and (iii) Quaternary but not Holocene offset. Faults of the NMSZ were most clearly defined from current microseismicity and historical earthquakes. Correlation of earthquakes and faults is often obscure because most faults are strike-slip and leave little topographic expression of motion.

The three main shocks of the 1811–1812 earthquake sequence ruptured the three segments of the NMSZ system. On December 16, 1811, a **M** 8.1 earthquake with right-lateral strike-slip motion occurred on the southern arm of the system, along the Blytheville Arch. The main rupture was on the Bootheel lineament with a major aftershock on the Cottonwood Grove fault. On January 23, 1812, a **M** 7.8 earthquake with right lateral motion shook the region. Findings of REI (1999) place this earthquake on the East Prairie fault, largely on the basis of a discussion of fault mechanics and historical accounts of the epicenter location. On February 7, 1812, a **M** 8.0 earthquake with thrust motion ruptured the Reelfoot fault across the Mississippi River at New Madrid, Tennessee. This earthquake was located on the Reelfoot fault from detailed historical accounts of epicenter location, related surface deformation that severely affected the flow of the Mississippi river, and microseismicity data. According to findings of the REI (1999) report, the rupture of the Reelfoot fault occurred along a cumulative fault rupture length of 75 km, and included a component of left-lateral strike-slip faulting on fault segments just west of the main thrust plane [see figure A-18b in appendix A of REI (1999)].

Findings of REI (1999) note three faults with evidence of Holocene displacement. These are the Ridgely, Crittenden County, and Commerce (Benton Hills) faults. All three show evidence for oblique (transpressional) right-lateral strike-slip displacements acting on reactivated rift-bounding normal faults. The remaining twelve faults in the list of possible faults show evidence of Quaternary activity but no direct evidence of Holocene offsets.

To account for seismicity not directly tied to specific faults, REI (1999) developed four generalized seismic source zones. These include a zone to account for the possible extension of the East Prairie and Commerce faults, and background zones for the seismicity along the flanks of the Reelfoot Rift and within the diffuse WVSZ.

Of the 23 potential sources identified in the REI (1999) findings—19 fault sources and 4 area sources—9 were incorporated into the hazard assessment as distinct seismic sources. The remaining faults and seismic zones identified were not considered significant to the PGDP seismic hazard because they were too small to generate significant magnitude earthquakes or their recurrence too infrequent compared to other faults of the region to contribute to the hazard. Fault sources are the East Prairie, Reelfoot, and Blytheville Arch faults, and source zones for the East Prairie fault extension, WVSZ, Rough Creek Graben, and an eastern and western background zone [see table 3-1 of REI (1999)].

Pursuant to NRC guidance and criteria (1995, 1997a,b, 1998b,c), this section of the PGDP study is acceptable because the historic earthquake activity identified in the REI (1999) report is consistently correlated to specific geological structures or tectonic provinces. For each earthquake or group of related earthquakes, the rationale for relating them to a specific geological structure or tectonic province was developed and is technically defensible. The rationale for specific fault or tectonic province association included references to relevant geological or geophysical data or tectonic interpretations.

Where correlations between earthquakes and geological features were not conclusive, alternative interpretations were presented with discussion about how the alternative interpretations affect the overall seismic hazard. For example, the REI (1999) report developed alternatives for the geometry (length and location) of the East Prairie fault and the East Prairie fault extension in logic trees that were incorporated into the PSHA logic tree. Justification of how these alternatives are weighted in the logic tree are adequately discussed. According to section 2.5.2.1 of NUREG–0800 (Nuclear Regulatory Commission, 1997b), the analysis was augmented by regional geological and seismicity maps (at the same scale) to show correlation of tectonic provinces, earthquake epicenters, and associated geologic or tectonic structures.

3.1.4 Maximum Earthquake Potential

Maximum earthquake potential for each source (Mmax) was determined in the REI (1999) report by considering fault lengths, from which maximum magnitudes are derived from scaling relationships (Wells and Coppersmith, 1994), the historical earthquake record, and considerations of static stress drop (Johnston, 1996). To account for uncertainties on Mmax, a range of viable alternative interpretations of magnitude with recurrence were developed for the fault source [e.g., A-14 in appendix A of REI (1999)]. These weighted alternatives were then incorporated into the seismic hazard analyses, consistent with the criteria established in the Paducah RP (Chen et al., 1998).

Pursuant to NRC guidance and criteria (1995, 1997a,b, 1998c), this section of the PGDP study is acceptable because the REI (1999) report followed the PSHA methodology, as outlined in the recommendations given by the SSHAC (1997).

3.2 EARTHQUAKE RECURRENCE CHARACTERISTICS

This section of the PGDP study is acceptable because seismic activity and recurrence relationships of fault and tectonic sources that could affect the determination of the peak ground motion for the 250-yr return period and the estimation of the return period for the 0.15g event were adequately characterized and determined. Adequate determination of the seismic activity and recurrence included (i) characterization of the seismic activity rate for each capable source, either as regional activity rate, slip rate, or recurrence rate; (ii) determination of whether the seismic activity, especially the maximum earthquakes, is temporally independent or occurs as clustered events; and (iii) development of a magnitude-recurrence model for each capable source. The reviews for each of these facets of earthquake recurrence and seismic activity are described in detail in the following sections. The review of earthquake recurrence characteristics considered differences between specific provisions of the DOE Compliance Plan for the PGDP and the regulatory requirements for nuclear power plants. As stated in section 2.1, the PGDP lies within the NMSZ, which is geographically east of the 105° west longitude cutoff for Central and Eastern United States sites. However, following NRC Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a), evaluation of the seismic hazard at the PGDP followed procedures normally applied to the Western United States.

3.2.1 Seismic Activity

Findings of REI (1999) used a combination of historic and paleoseismic data to generate recurrence parameters for the seismic sources. Uncertainties associated with these parameters were addressed by considering additional information from recent geodetic data (e.g., Weber et al., 1998) and strain rate limitations for this portion of the North American tectonic plate. These uncertainties were addressed in alternative branches of logic trees, with appropriate and defensible weighting, and incorporated into the overall PSHA. For example, trenching results from the Reelfoot fault indicate four large earthquakes in the last 2,000 yr (Schweig and VanArsdale, 1996; Kelson et al., 1996). This geologic record suggests a recurrence interval of about 500 yr. In REI (1999, appendix A), VanArsdale and Johnston point out that, if these were all **M** 8 earthquakes, the strain rate across the region would be extremely high, well outside the values currently recorded by geodetic surveys (Weber et al., 1998), or those deemed credible for the tectonic setting of the PGDP. To account for this uncertainty, three branches of the PSHA logic tree were developed based on three alternative interpretations of the **M**max and recurrence interval. These three branches were then incorporated into the PGDP PSHA logic tree. One branch allowed for large **M** 8 earthquakes with a 500-yr recurrence interval. The second also allowed for **M** 8 earthquakes, but less frequently (once every 1,000 yr). The third branch allowed for slightly smaller earthquakes **M** 7.5–8.0, keeping the 500-yr recurrence interval.

Pursuant to NRC guidance and criteria (1995, 1997a,b, 1998c), this section of the PGDP study is acceptable because the seismic activity of the capable seismic sources has been adequately characterized. Fault or tectonic source activity was estimated from the historical seismic, paleoseismic, geological, and geophysical information following guidelines described in detail in appendix D of Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a).

As discussed above, valid alternatives, based on technically defensible interpretations of fault activity (e.g., in comparisons of geodetic and paleoseismic results of strain rates) were discussed, including how the alternatives affect the overall estimation of the seismic hazard. These alternatives were then correctly incorporated into the PSHA logic tree, and justification of how these alternatives were weighted in that logic tree was discussed.

3.2.2 Clustered Earthquakes

One of the critical aspects of the seismicity in the NMSZ is the question of possible clustered activity. The 1811–1812 earthquakes were clearly a cluster of three main shocks, and there is ample geological and geophysical evidence provided by VanArsdale and Johnston [appendix A of REI (1999)] to show that pattern is characteristic of the zone. For example, regional paleoseismic data specific to the Reelfoot fault (Kelson et al., 1996) correlate with regional liquefaction chronologies, suggesting large clustered activity once every 500 yr. Theoretical consideration of the effect of assuming clustered activity in the PSHA shows that it is more conservative than assuming three single independent events [see answer to question 1 in appendix D of REI (1999)].

Pursuant to NRC guidance and criteria (1995, 1997a,b, 1998c), this section of the PGDP study is acceptable because recurrence of earthquakes was adequately characterized. The implication of clustering was incorporated into estimates of earthquake recurrence. Alternatives were discussed, including how the alternatives affect the overall estimation of the seismic hazard.

3.2.3 Magnitude-Recurrence Models

A composite exponential-characteristic recurrence model was developed for each source in REI (1999). The exponential portion was based on the maximum likelihood analysis of the historic seismic record. The characteristic portion was based on paleoseismic and geological information about maximum **M**. This is now standard practice in PSHA studies (Senior Seismic Hazard Analysis Committee, 1997).

Pursuant to NRC guidance and criteria (1995, 1997a,b, 1998c), this section of the PGDP study is acceptable because magnitude-recurrence models for the capable seismic sources were adequately developed and discussed. Magnitude-recurrence models incorporated exponential (Gutenberg and Richter, 1954) and characteristic (Schwartz and Coppersmith, 1984) models. Technical justification was presented based on interpretations of the historic seismic record, paleoseismic evidence, and geological and geophysical analyses in support of the magnitude-recurrence models for each source. Uncertainties were accounted for in the magnitude-recurrence models for each source.

3.3 GROUND-MOTION ESTIMATES

Pursuant to Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a), ground-motion estimates are acceptable if (i) the estimates are made for rock conditions in a free field or by assuming hypothetical rock conditions for a non-rock site, (ii) site-specific responses (such as soil amplification and deamplification) are analyzed considering uncertainties in site-specific geotechnical properties, and (iii) characterization of ground motion (including treatment of uncertainties) is consistent with recommendations of the SSHAC (1997). According to the SSHAC (1997), ground motion should be characterized by (i) a spectrum of the natural logarithm of the median of the ground-motion parameter determined as a function of magnitude and distance at multiple frequencies, and (ii) the standard deviation of the natural logarithm of the ground-motion parameter. The standard deviation could be a function of magnitude, distance, and frequency, as applicable. Specific acceptance criteria for ground-motion estimates are detailed in the RP (Chen et al., 1998). REI (1999) ground-motion estimates are evaluated against these specific acceptance criteria in the following sections. The review of ground-motion estimates considered the differences between regulatory requirements for the PGDP and for nuclear power plants, mainly because the

PSHA for the PGDP follows special provisions in the DOE compliance plan (Toelle, 1997) as detailed in chapter 1 of the RP (Chen et al., 1998).

3.3.1 Attenuation Functions for Rock

Calculation of ground motion for rock condition in a free field (i.e., assuming hypothetical rock conditions) is based on the attenuation models developed by EPRI (1993) for Central and Eastern North America (CENA) (Risk Engineering Inc., 1999). The ground motions used for developing these attenuation models were numerically simulated ground motions computed using the stochastic point source model (also known as the Band-Limited-White-Noise or BLWN model) (Hanks and McGuire, 1981; Boore, 1983, 1986; Silva, 1991). The use of the stochastic model or numerically simulated ground motions in CENA instead of recorded ground motions is consistent with common practice and the state of knowledge, because sufficient strong motion data are lacking in this tectonic regime due to low seismicity rates. The stochastic model of EPRI (1993) was tested against recorded motions for several large-magnitude events, including the 1989 Loma Prieta (**M** 6.9), 1987 Whittier Narrows (**M** 5.9), 1985 Nahanni (**M** 6.8), and 1988 Saguenay (**M** 5.8) earthquakes. This comparison showed that the predictions adequately match the recorded ground motions for the frequency, distance, and magnitude range of interest (Electric Power Research Institute, 1993). The models are applicable to a frequency range of 1 to 35 Hz, distances of 1 to 500 km (with emphasis on distances of 1 to 100 km), and a **M** of 5 to 8. These are consistent with applicable ranges of frequency, distance, and magnitude (Senior Seismic Hazard Analysis Committee, 1997).

The EPRI attenuation models include those for PGA and peak spectral acceleration (PSA). This satisfies the requirement described in the RP (Chen et al., 1998) that representation of seismic hazard as a function of structural frequency (hazard spectrum) should be obtained directly from attenuation functions that predict spectral acceleration as a function of structural frequency, rather than a fixed spectral shape anchored to a particular value of the PGA. Accordingly, the design spectrum should be developed based on the hazard spectrum.

Model parameters were developed by REI (1999) following an extensive analysis of ground-motion data and other relevant data, and by fitting these data to the functional forms of the attenuation models. Separate sets of coefficients were obtained for the Midcontinent and Gulf crustal regions. The set for Midcontinent was used in the PGDP seismic hazard analyses (Risk Engineering, Inc., 1999). As discussed previously, ground-motion data were numerically simulated using the stochastic point source model. The simulation is specific to the CENA and considered the tectonic and earthquake source characteristics in CENA. The CNWRA reviewers consider these attenuation models and associated parameters appropriate for tectonic characteristics affecting the PGDP, as evaluated in section 3.1.

The EPRI (1993) attenuation models applied by the REI (1999) to the PSHA at the PGDP are in terms of **M**, consistent with the magnitude scale used in source characterizations discussed in section 3.1. The definition of distance in the attenuation models is distance to a point source for area seismic sources. For fault sources, especially for calculations involving the faults in the NMSZ and the East Prairie extension, REI (1999) modified the distance term in the original EPRI (1993) attenuation models to include magnitude-saturation effect (or extended-source effect) and used the closest horizontal distance to the rupture surface. Extended-source effects were introduced using two approaches, namely empirical (Atkinson and Silva, 1997) and modeling (Risk Engineering, Inc., 1993). Sensitivity results show that the median ground-motion amplitude is the largest using the no-saturation option and the smallest using the modeling approach. To include uncertainties, each of these approaches was assigned a weight of 0.4 and the no-saturation option was assigned a weight of 0.2. Such consideration of extended-source effects is consistent with common practice for large tectonic earthquakes (e.g., these effects are found to be important and used in nearly all attenuation models for California or other active tectonic regions) and with recommendations of SSHAC (1997).

3.3.2 Site-Response Models

The methodology used in the site-response calculation for the PGDP is based on a random-vibrations theory (RVT), (e.g., Vanmarcke, 1976; Boore, 1983) as described in EPRI (1993). In the RVT approach, the control motion (horizontally polarized shear-wave, or SH wave) power spectrum is propagated through the one-dimensional soil profile using the plane-wave propagators of Silva (1976). The treatment of material nonlinearities is achieved using the equivalent-linear approach introduced by Seed and Idriss (1970), similar to the approach used to treat material nonlinearity in SHAKE (Schnabel et al., 1972). The difference between the RVT based equivalent-linear approach and the equivalent-linear approach used in SHAKE is that the RVT method is based purely on the frequency domain, which obviates a time domain control motion and eliminates the need for multiple time history analyses. The RVT based equivalent linear approach can be considered more robust because the estimates of peak shear-strain as well as oscillator response are, as a result of the random process theory, fundamentally probabilistic in nature and parametric uncertainties can be assessed through a Monte Carlo approach by randomly varying dynamic material properties. As a result, the RVT-based equivalent linear approach can result in mean as well as percentiles of smooth response spectra or amplification factors at the surface of the site.

The procedure for generating stochastic power spectrum, computing equivalent-linear layered-soil response, and estimating peak time domain values is incorporated into a computer code known as RASCALS (Electric Power Research Institute, 1993). In applying the EPRI approach to the PGDP, REI (1999) also used the stochastic shear-wave velocity model of Silva (1997) to characterize uncertainty in the shear-wave velocity profile beneath the site by considering multiple artificial profiles. The stochastic shear-wave velocity model of Silva (1997) is based on statistical analysis of approximately 500 measured velocity profiles. In REI (1999) calculations, the soil-column properties were obtained by Staub and Wang (1991). The best-estimate depth to bedrock was taken as the average depth to the limestone basement from the two existing boreholes that reached the bedrock (Staub and Wang, 1991). The modulus and damping degradation curves were those of EPRI (1993) for generic CENA soil sites. The randomization of profiles used the measured site-specific profile (Staub and Wang, 1991), together with the correlation model for USGS Soil Category A in appendix C of Silva (1997). The depth to bedrock was treated as uniformly distributed within ± 50 ft of the average bedrock depth.

The CNWRA evaluation found the REI (1999) soil site-response model acceptable because it adequately considered the expected modifications of the ground motions for the local site conditions, including the geologic materials below the surface of the site. It sufficiently considered soil nonlinearity and property uncertainties. The considerations and treatment of soil nonlinearity and property uncertainties are consistent with current engineering practice and the state of knowledge. Specifically, it follows strategies and methodologies outlined in EPRI (1993) with modification of the randomization scheme for treating uncertainties in material dynamic properties following the methodologies proposed by Silva (1997).

Vertical motions have received little attention for soil sites in the Central and Eastern United States. Neither specific recommendations nor guidelines regarding applications to eastern sites have been developed in the existing NRC regulations or regulatory guidance documents (Nuclear Regulatory Commission, 1973, 1997a,b, 1998b,c; Senior Seismic Hazard Analysis Committee, 1997). The only specific recommendations for vertical-to-horizontal ratios which consider the differences in typical western and eastern strong ground motions are those of EPRI (1993). EPRI (1993) also proposed a preliminary computational approach.

The REI (1999) estimate of vertical ground motion at the PGDP utilized the computational approach of EPRI (1993), in which the calculations of vertical and horizontal ground motions on soil are independent. In this approach, vertical motions at the surface are composed of inclined P and SV waves, with angles of incidence determined by the depth and distance to the source and the crustal velocity structure beneath the site. Soil nonlinearity is neglected. Randomization of Poisson's ratio is performed in addition to randomization of soil velocity profiles. Randomization of distances is also performed because SV motions are sensitive to the incidence angle. Randomization used the scheme proposed by Silva (1997). Such calculations resulted in ratios of vertical motion on soil [V(soil)] versus horizontal motion on rock [H(rock)] as a function of frequency for two selected return periods (250 and 1,000 yr). V(soil)/H(rock) ratios for rock spectral accelerations lower than the 250-yr rock spectral acceleration were assumed equal to the 250-yr V(soil)/H(rock) ratio. V(soil)/H(rock) ratios for rock spectral accelerations higher than the 1,000-yr rock spectral acceleration were assumed equal to the 1,000-yr V(soil)/H(rock) ratio. Ratios for intermediate values of the rock spectral acceleration were obtained by linear interpolation in log-log space. In addition, values of V(soil)/H(rock) for low frequencies were increased where it was necessary to maintain a minimum V(soil)/H(soil) ratio of 2/3. The V(soil)/H(rock) ratios were used to calculate vertical soil spectra based on horizontal motion on rock. These calculations were performed by REI subcontractor, Pacific Engineering, Inc. using its software RASCALS (version 2.0).

As stated in the RP (Chen et al., 1998), no generally agreed-upon procedures for calculating vertical motion on soil can be promulgated at this time. The professional judgement of the reviewers was used in evaluating the methods of analysis. The evaluation found REI calculation of vertical ground motion on soil at the PGDP technically sound. Site-specific data and state of knowledge were sufficiently considered. Such calculation provided sufficient assurance that all the aspects important to a conservative estimate of vertical ground motion were taken into consideration and all applicable regulatory requirements were met.

3.3.3 Uncertainties

Uncertainties in the ground motion estimate at the PGDP developed by REI (1999) were derived by considering the uncertainties in parameter values, as well as uncertainties associated with the ground-motion model (Risk Engineering, Inc., 1999). According to Toro et al. (1997), the combined effect of all parametric uncertainties is obtained by performing statistics on the residuals from the least-squares fit to model predictions. The epistemic uncertainty is determined following estimation of aleatory uncertainty. The total aleatory uncertainty in ground-motion amplitude for a given magnitude and distance is decomposed into a magnitude-dependent term and a distance-dependent term. The magnitude-dependent aleatory uncertainty is approximated by three linear segments, defined by its values for three magnitudes. Values for other magnitudes are obtained by linear interpolation. The distance-dependent aleatory uncertainty is approximately constant for $R_{jb} < 5$ km, varies linearly between 5 and 20 km, and is constant for $R_{jb} > 20$ km (R_{jb} is the closest horizontal distance to the vertical projection of the earthquake rupture in km, also known as Joyner-Boore distance).

A unique feature of the EPRI (1993) ground-motion study is that it produced not only a best-estimate attenuation equation, but also a quantification of the associated epistemic uncertainty. This epistemic uncertainty is characterized by a standard deviation (in natural-log units) that is approximately linear in magnitude and independent of distance (Electric Power Research Institute, 1993; Toro et al., 1997). Epistemic uncertainty includes uncertainties due to different modeling approaches used by different members of the EPRI ground-motion team, uncertainties in the physical parameters of the model, and limitations in the modeling approach. Naturally, this epistemic uncertainty is the same as one captures by using multiple attenuation equations developed by different experts. Thus, REI (1999) claims that the EPRI attenuation equations and their associated uncertainties may be used in place of multiple attenuation equations developed by different experts. In PSHA, this uncertainty is accounted for by replacing the normal distribution of the uncertainty term with four-point discrete distribution that is described by values from a discrete approximation to a standard normal distribution and associated weights (Electric Power Research Institute, 1993; Toro et al., 1997; Risk Engineering, Inc., 1999). This approach resulted in four sets of attenuation equations that differ from the median attenuation equation in the intercept and the linear magnitude term.

The REI (1999) estimates of total uncertainty in ground motion are acceptable according to staff evaluation. Such estimates are realistic and incorporate significant sources of uncertainty, including the existence of alternative models and the possibility of alternative interpretations of the existing data. In addition, the REI (1999) estimates of total uncertainty in ground motion followed the SSHAC (1997) recommendations to partition total uncertainty into aleatory and epistemic components, as well as the use of quantitative procedures for the development of uncertainty estimates. Such a partition is consistent with the current practice.

The site-response model considered uncertainties in shear-wave velocity profile and in the modulus reduction and hysteretic damping curves. Vertical motion calculation considered uncertainties in shear-wave velocity profile, Poisson's ratio, and distances. Uncertainties in both the site-response model and vertical motion calculation were quantified using the randomization approach proposed by Silva (1997). Again, the treatment of uncertainties in the site-response model and in the vertical motion calculation is adequate and consistent with current engineering practice and state of knowledge.

3.4 HAZARD CALCULATION AND PRESENTATION

Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a) calls for a site-specific PSHA using procedures similar to those normally applied in the Western United States for sites in tectonically active areas of the Central and Eastern United States, such as the NMSZ. The site-specific PSHA for PGDP is acceptable if (i) principles and procedures for structuring and implementing the PSHA are technically sound and consistent with those for the corresponding level of PSHA studies recommended by the SSHAC (1997) and those in Regulatory Guide 1.165 and its appendices (Nuclear Regulatory Commission, 1997a), (ii) treatment of uncertainties is consistent throughout the study and follows methodologies recommended by the SSHAC (1997), (iii) hazard calculation incorporates important factors and significant uncertainties associated with source characteristics and ground-motion estimates, and (iv) hazard results are complete and the presentation of hazard results is logical and comprehensible. In addition, for the site-specific PSHA for PGDP to be acceptable, seismic source and earthquake recurrence characteristics described in sections 3.1 and 3.2 and ground-motion estimates described in section 3.3 should be acceptable. Specific acceptance criteria for hazard calculation and presentation are detailed in the RP (Chen et al., 1998). REI (1999) hazard calculations are evaluated against these specific acceptance criteria in the following sections. The review of hazard calculation and presentation considered the differences between regulatory requirements for the PGDP and for nuclear power plants.

3.4.1 Structure of the Probabilistic Seismic Hazard Analysis

The REI (1999) seismic report describes the purpose of its PSHA study at the PGDP as two-fold: (i) to produce hazard results that will be used to make decisions regarding seismic safety and levels of seismic design at the facility, and (ii) to provide a guideline for seismic hazard study in the Central and Eastern United States. It is to be noted that the CNWRA evaluation applies only to the REI PSHA specific to the PGDP for design purposes. It does not apply or endorse the use of the REI PSHA as a guideline for other Central and Eastern United States sites or any other purposes. Although PGDP is in Central and Eastern United States, it has its unique characteristics due to high seismic activity. Also, according to Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a), seismic hazard at New Madrid should be investigated following procedures normally applied to the Western United States.

As stated in SSHAC (1997), the success of a PSHA project is principally determined by how it is structured and implemented to derive input; in particular, how this implementation accounts for different technical interpretations of the available evidence and uncertainties. The REI (1999) study is comparable to a level 2 study defined by the SSHAC (1997) in which the technical investigator (TI) interacts with proponents and resource experts to identify issues and interpretations, and estimates community distribution. As defined by SSHAC (1997), a proponent expert is an expert who advocates a particular hypothesis or technical position, and a resource expert is a technical expert with specific knowledge of a particular data set of importance to a PSHA. In the REI (1999) study, the TI (i.e., REI) used a sole source (University of Memphis) as its resource expert for characterization of seismic source and earthquake recurrence. The resource expert conducted geological and seismological studies on the New Madrid and Wabash regions and developed interpretations based on these studies to provide logic tree options and parameters for seismic source and earthquake recurrence characterization, as evaluated in detail in sections 3.1 and 3.2. In estimating seismic ground motion, the TI used the EPRI (1993) attenuation equations for rock, with treatment of uncertainties extended by Toro et al. (1997). In the EPRI (1993) study, ground-motion estimates were developed using a weighted combination of different modeling approaches as represented by various members of the EPRI ground-motion team. The resultant ground-motion model is a best-estimate attenuation equation and a quantification of the associated epistemic uncertainty, equivalent to the epistemic uncertainty that one captures by using multiple attenuation equations developed by different experts. The CNWRA reviewers found the overall structuring and implementation of the REI seismic study acceptable and consistent with the basic principles and procedures recommended by the SSHAC (1997) and Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a).

The PSHA structuring is poorly presented in the REI (1999) report. In some cases, a statement of the bases for input, such as weights assigned to different branches of a logic tree, is not adequately discussed in the REI (1999) report; however, it was discussed during a meeting at the REI offices in Boulder, Colorado. Although state of knowledge approaches (e.g., randomization in the site-response model and vertical motion calculation) were applied in the analyses, their implementation was not clearly explained in the REI (1999) report. Calculations done by subcontractors on soil amplification factors and vertical motion are not adequately presented. The CNWRA reviewers consider these deficiencies to be mainly presentation shortcomings and do not affect the acceptance of the overall structuring and implementation of the REI seismic study. However, these deficiencies did make the review process less efficient, since relevant information had to be obtained by reviewing open literature and various reference technical reports cited by REI (1999), and through oral technical discussions.

3.4.2 Uncertainties

In the REI seismic study, uncertainties in source characterization and earthquake recurrence characteristics were quantified by considering multiple alternative geometries, multiple magnitude-recurrence parameters, and multiple maximum magnitudes as evaluated in sections 3.1 and 3.2. In ground-motion attenuation for rock, the epistemic uncertainty captured by the EPRI (1993) attenuation equations as a normal distribution was replaced with a four-point discrete distribution that is described by values from a discrete approximation to a standard normal distribution and associated weight, resulting in four alternative sets of attenuation equations that represent a range of models for the source and path characteristics of earthquakes in the Central and Eastern United States. In the site-specific model and vertical motion calculation, uncertainties were calculated using the randomization approach proposed by Silva (1997). Detailed evaluation of uncertainties in ground motion is given in section 3.3.3.

Overall, the treatment of uncertainties by the REI (1999) report is acceptable because it complies with the recommendations for treatment of aleatory and epistemic uncertainties described in SSHAC (1997) and is consistent with common engineering practice and state of knowledge. The propagation of these uncertainties and consistency of the application of these uncertainties in total hazard calculation is further evaluated in section 3.4.3.

3.4.3 Probabilistic Seismic Hazard Analysis Calculation

The PGDP PSHA (Risk Engineering, Inc., 1999) uses the methodology and basic equations well established in the literature (Cornell, 1968, 1971; Der Kiureghian, 1975; McGuire, 1976, 1978; and Electric Power Research Institute, 1988, 1993). In the PSHA methodology, three basic inputs are specified, namely source geometry, seismicity, and ground-motion attenuation. Source geometry and a relationship between rupture size and magnitude determine the conditional probability distribution of distance from the earthquake rupture to the site for a given magnitude. Seismicity is characterized by the rate of occurrence and magnitude distribution of earthquakes occurring in each source, including the maximum magnitude that a source can produce. In the REI (1999) study, only earthquakes with $\mathbf{M} \geq 5$ were considered. Smaller earthquakes were assumed to produce no damage to engineered structures, regardless of the ground-motion amplitudes they generated. Ground-motion attenuation is a relationship that allows the estimation of ground-motion amplitude at the site as a function of earthquake magnitude and source-to-site distance. REI ground-motion characterization included both a median amplitude and a standard deviation that describes the anticipated site-to-site and event-to-event scatter. Detailed evaluations of the characterization of these three basic inputs are discussed in sections 3.1 through 3.3, respectively.

As evaluated in section 3.2, the REI (1999) study incorporated the assumption that large earthquakes on any NMSZ segment are followed by large earthquakes in the other two segments, by treating the three NMSZ segments (the Blytheville Arch, Reelfoot fault, and East Prairie) as one special source. The formulation used to address temporal clustering of large earthquakes in the NMSZ is technically sound.

The methodologies and formulations for hazard calculation used by the REI (1999) study, including those for addressing temporal clustering characteristics in the NMSZ, are acceptable because they are consistent with site-specific information as evaluated in sections 3.1 through 3.3 and the state-of-the-art methodology as established in the literature (e.g., Cornell, 1968, 1971; Der Kiureghian, 1975; McGuire; 1976, 1978; Electric Power Research Institute, 1988, 1993). Distribution functions characterizing source geometry, seismicity, and attenuation functions are appropriate for the site-specific conditions and are consistent with the evaluation described in sections 3.1 through 3.3, respectively.

Consistent with recommendations of the SSHAC (1997) and other advanced seismic hazard studies, the REI (1999) seismic hazard calculation treated aleatory and epistemic uncertainties differently. Aleatory uncertainties were integrated to get a single hazard curve, whereas epistemic uncertainties were expressed by multiple assumptions, hypotheses, models, and parameter values. These multiple interpretations were propagated through the analysis using a logic tree technique, resulting in a suite of hazard curves and their associated weights from which the statistical summaries of exceedance probability for each ground-motion amplitude were calculated. These include mean, median, and percentile seismic hazard curves.

The CNWRA evaluation found the REI (1999) calculation of the PSHA at the PGDP acceptable, because (i) it integrates the seismic source and earthquake recurrence characteristics and ground-motion estimates that are consistent with those evaluated in sections 3.1 through 3.3, and (ii) it includes quantification of significant epistemic uncertainties in the seismic source and ground-motion inputs. Two nested steps were taken in the calculation and methodology for assessing the estimated seismic hazard and quantifying its epistemic uncertainty, consistent with those recommended by SSHAC (1997). These two steps were: (i) basic calculations of a single-source seismic hazard curve by integrating the source characterization with a specific set of ground-motion distributions, and (ii) development of a probability (epistemic uncertainty) distribution for the estimated seismic hazard by the propagation of the epistemic uncertainties associated with the seismic source and earthquake recurrence characteristics and ground-motion distributions.

The CNWRA evaluation of the first step calculation found that (i) all of the basic hazard identities were included and properly interpreted in the calculation, (ii) numerical integration methods were appropriate, (iii) seismic source zone geometry was well developed and tracked, and (iv) evaluation of the probability density function of the distance was technically sound. In review of the second step, the CNWRA reviewers evaluation confirmed that (i) descriptions of the epistemic uncertainties associated with the inputs were consistent with those evaluated in sections 3.1 through 3.3, (ii) uncertainties were adequately quantified, (iii) potential correlations between the uncertainties were recognized and properly treated, and (iv) methods for epistemic uncertainty propagation were appropriate and consistent with those described in SSHAC (1997).

3.4.4 Hazard Results

For rock condition, the basic PSHA results presented in the REI (1999) seismic report included (i) the mean and median hazard curves for the PGA and for PSAs at 0.5, 1.0, 2.5, 5, 10, 25, and 35 Hz and 5 percent damping, representing the central tendency of the hazard; (ii) 15–85 percentile hazard curves for the PGA and for PSAs at 0.5, 1.0, 2.5, 5, 10, 25, and 35 Hz and 5 percent damping, representing epistemic uncertainty in seismic hazard; and (iii) median and mean uniform-hazard spectra for annual exceedance probabilities of 4×10^{-3}, 2×10^{-3}, 1×10^{-3}, and 2×10^{-4} (corresponding to average return periods of 250, 500, 1,000, and 5,000 yr). At a return period of 250 yr, the median PGA on rock is 0.093g and the mean PGA on rock is 0.098g. The shape of the median and mean uniform-hazard spectra for various annual exceedance probabilities are typical of Central and Eastern United States ground motions, with significant energy at frequencies in excess of 10 Hz.

The results deaggregated by source on rock condition are also presented for the PGA and for a 1-Hz PSA, showing the contributions of various seismic sources to the mean total hazard. At return periods of 250 yr or longer, more than half the hazard comes from the East Prairie extension and the East Prairie fault.

Next in importance are other NMSZ faults (e.g., Blytheville arch, Reelfoot fault). The WVSZ has a small contribution to the hazard. The results deaggregated by magnitude, distance, and aleatory uncertainties are presented for the PGA and for 1-Hz PSAs at 250- and 1,000-yr return periods, respectively. For the 250-yr return period and PGA, small and moderate earthquakes on the East Prairie extension contribute approximately the same amount as large earthquakes on the East Prairie extension, East Prairie, and other NMSZ faults. For a 250-yr return period and 1-Hz PSA, large earthquakes dominate the seismic hazard.

For soil condition, median and mean uniform-hazard spectra for horizontal and vertical motions are presented for annual exceedance probabilities of 4×10^{-3}, 2×10^{-3}, 1×10^{-3}, and 2×10^{-4} (corresponding to average return periods of 250, 500, 1,000, and 5,000 yr) and for various damping ratios (2, 5, 7, and 10 percent). At a return period of 250 yr, the mean and median horizontal PGA are 0.165g and 0.159g, respectively, and the mean and median vertical PGA are 0.110g and 0.106g, respectively.

The presentation of these seismic hazard results is acceptable because it follows the content and format outlined in SSHAC (1997) and includes a complete set of results that are defined as required by SSHAC (1997) for both rock and soil site conditions. As indicated earlier, the mean horizontal PGA for the seismic event with a 250-yr return period at the PGDP (on soil) is evaluated to be 0.165g. This estimate is greater than 0.15g. The mean probability of exceeding a horizontal PGA of 0.15g on soil was estimated to be 4.5×10^{-3}, corresponding to an average return period of 220 yr. This evaluation satisfies the requirement of the Compliance Plan as indicated in chapter 1 of this report.

4 EVALUATION FINDINGS

The CNWRA evaluation of the PSHA performed by the REI (1999), as detailed in chapter 3, found that the information provided and investigations performed support the REI conclusions regarding the seismic ground-motion hazard at the PGDP. The evaluation by the CNWRA reviewers confirmed that (i) the PSHA for the PGDP meets the requirements of the applicable NRC regulations and regulatory guides as detailed in chapter 2, (ii) the estimation of a PGA of 0.165g for the 250-yr return period earthquake and the return period of 220 yr for the 0.15g earthquake is adequate, and (iii) the estimation of the uniform hazard spectra for the 250-yr return period earthquake is adequate for design purpose for the PGDP.

In addition to the above overall conclusion, specific evaluations for each of the technical aspects are detailed in chapter 3. These technical aspects include (i) seismic source characterization, (ii) earthquake recurrence characteristics, (iii) ground-motion estimates, and (iv) hazard calculation and presentation. Evaluation findings for each of these aspects are summarized as follows.

- Seismic source characterization. In the review of the seismic source characterization, the CNWRA reviewers have considered pertinent information included in REI (1999), obtained from technical exchanges, and collected from available literature. The CNWRA reviewers find this section of the PGDP study acceptable in that potential sources of seismicity that affect the determination of the peak ground motion for the 250-yr return period and the estimation of the return period for the 0.15g event have been adequately determined. Specific technical evaluations that support this summary finding are detailed in section 3.1 of this review report with regard to geologic and tectonic setting of the site and region, historical seismic data, correlation of earthquake activity with geologic structures or tectonic provinces, and maximum earthquake potential, including consideration of available USGS data.

- Earthquake recurrence characteristics. In the review of the earthquake recurrence characteristics, the CNWRA reviewers have considered pertinent information included in REI (1999), obtained from technical exchanges, and collected from available literature. The CNWRA reviewers find this section of the REI (1999) report acceptable in that seismic activity and recurrence relationships of potential seismic sources (both fault and areal sources) that affect the determination of the peak ground motion for the 250-yr return period and the estimation of the return period for the 0.15g event have been adequately characterized and determined. Specific technical evaluations that support this summary finding are detailed in section 3.2 of this review of the REI (1999) report with regard to characterization of seismic activity for each capable source, possible temporal clustering of earthquakes, and development of magnitude-recurrence models for each capable source, including consideration of available USGS data.

- Ground-motion estimates. In the review of the ground-motion estimates, the CNWRA reviewers have evaluated the methodology for site-specific ground-motion estimates used by REI (1999), examined the consistency of the REI approach with the state-of-knowledge, and considered existing site-specific geotechnical data and the applicable ground-motion database. The reviewers find this section of the REI study acceptable because the ground-motion attenuation functions are appropriate for the tectonic regime, source types, and tectonic characteristics at the PGDP; and consideration of the site-specific response is conservative for the estimation of the PGA for the 250-yr return period earthquake, the return period for the earthquake with 0.15g PGA, and the corresponding uniform hazard spectra. The REI ground-motion estimates and site-specific calculations are acceptable also because they are based on EPRI (1993) ground-motion attenuation equations and strategies for site-specific considerations and uncertainty treatment and the PSHA methods and the data developed by the EPRI (1993) for the Central and Eastern United States were previously reviewed and accepted by NRC, according to Regulatory Guide 1.165 (Nuclear Regulatory Commission, 1997a).

- Hazard calculation and presentation. In the review of the hazard calculation and presentation, the CNWRA reviewers have evaluated the REI (1999) methodology for calculating the hazard and addressing uncertainties, surveyed the state-of-the-art PSHA literature, examined applicable NRC regulations and regulatory guidance documents, and considered the evaluation findings on seismic source characterization, earthquake recurrence characteristics, and ground-motion estimates. The CNWRA reviewers find this section of the PGDP study acceptable because the methodology and its application are technically sound and all input and associated uncertainties have been taken into sufficient consideration in the estimation of the PGA for the 250-yr return period earthquake, the return period for the earthquake with 0.15g PGA, and the corresponding uniform hazard spectra. However, the PSHA structuring is poorly presented in the REI (1999) seismic report. In some cases, the bases for selections of logic tree branches and associated weights are not sufficiently stated. Implementation of some state of knowledge approaches in ground-motion estimations (e.g., in site-response models) is not sufficiently discussed. These shortcomings do not affect the acceptance of REI conclusions regarding the seismic ground-motion hazard at the PGDP. However, they made the review process less efficient and the understanding of REI PSHA more difficult since relevant information had to be obtained by other means and from other sources.

The CNWRA evaluation also included checking the consistency of the REI PSHA with applicable DOE documents such as guidelines for use of PSHA curves at DOE sites (U.S. Department of Energy, 1994a) and criteria for natural phenomena hazards design and evaluation for DOE facilities (U.S. Department of Energy, 1994b), although the CNWRA reviewers acceptance criteria did not rely on DOE standards as described in the RP (Chen et al., 1998) and, consequently, no detailed discussions were given in chapter 3. Evaluation by the CNWRA reviewers did not identify any significant inconsistency between the PSHA for the PGDP and the applicable DOE standards.

The CNWRA reviewer's opinion regarding the three overall issues related to the PSHA for the PGDP, as described in the RP (Chen et al., 1998) and in chapter 1, can be summarized as the following. It should be noted that some shortcomings are identified regarding the three overall issues related to the PSHA for the PGDP. These shortcomings do not affect the CNWRA acceptance of REI conclusions of seismic ground-motion hazard at the PGDP.

- Most of the significant concerns related to defining the seismic hazard and free-field surface ground motions at the PGDP were adequately addressed by REI (1999). It should be noted, however, the review was limited to the seismic ground-motion hazard specific to the PGDP. The review did not include the actual interpretation of the PSHA results for design purposes or evaluation of other hazards that may be induced by tectonic activity, such as surface faulting, instability of subsurface materials, liquefaction potential, and slope stability. For example, the East Prairie Extension Seismic Source Model [e.g., see figure 3-4 of REI (1998b)] predicts the possibility that faults of the East Prairie fault zone extend into southern Illinois. Recent mapping by Nelson et al. (1997) suggest that faults in the Fluorspar district in Illinois are active and could be the extension proposed in the REI model. Thus, although these new faults in Illinois are accounted for by the REI (1998b) seismic hazard assessment, they may also constitute a fault displacement hazard (i.e., surface faulting) at the PDGP site. It was beyond the scope of this review to assess fault displacement hazards at the PGDP site; however, current geological and geophysical investigations by the Illinois and Kentucky State Geological Surveys should further elucidate these potential hazards. These studies include seismic reflection data of faults thought to help focus groundwater flow of a contaminant plume under the site in Kentucky and trenching studies of fault zones in Illinois.[1] Again, results from these studies may indicate the need to characterize the potential of surface faulting hazard. However, evaluating surface faulting hazard is beyond the scope of the current review that is focused on ground-motion hazard.

- The approaches and results are consistent with the overall approaches defined in applicable NRC regulations and regulatory guidance documents (Nuclear Regulatory Commission. 1973, 1997a,b, 1998a,b,c; Senior Seismic Hazard Analysis Committee, 1997) and DOE standards (U.S. Department of Energy, 1994a,b). Again, although consistency with DOE standards was checked, the acceptance criteria used in the CNWRA review did not depend on consistency with DOE standards. Rather, acceptance criteria were established based on applicable NRC regulations and regulatory guidance documents.

- The hazard assessment presented in REI (1998b) satisfies established NRC requirements for the PGDP and provisions of the DOE Compliance Plan. This assessment is based on present state of knowledge and has incorporated known reasonable alternatives and uncertainties. The PGDP seismic hazard may require additional study, however, if new information about the tectonic or seismic setting of the site become available. The following list highlights some the areas of active research that should be followed for such new information.

  — The north portion of the NMSZ is very important in the PGDP PSHA; however, it is the most poorly understood, as indicated by the REI (1999) report. As more information about seismic source and earthquake recurrence characteristics is available in this area, the PSHA may need to be updated. This is especially true if future work shows structural linkage between the NMSZ and WVSZ. Additional geodetic surveys, especially global positioning system (GPS) surveys, will also be important. As GPS measurements are refined annually, uncertainty in crustal strains is reduced and a better understanding of the current strain conditions obtained.

  — Although the EPRI (1993) attenuation equations used by the REI (1999) report produced a quantification of the associated epistemic uncertainty that includes different modeling opinions of various members of the EPRI ground-motion team, this set of equations does not capture the full range of current opinions in the scientific community (e.g., Atkinson and Boore, 1997; Hwang and Huo, 1997). As pointed out in a RAI and in REI responses to the RAIs [appendix D, REI (1999)], Toro et al. (1997) and EPRI (1993) predict lower PGAs compared to those of Atkinson and Boore (1997) for smaller earthquakes at all distances and for larger earthquakes at distances greater than about 20 km. However, the EPRI (1993) equations predict high ground motion at lower frequency ($f < 2$ Hz). REI (1999) argues that EPRI (1993) equations are conservative because the most important frequencies for the PGDP facility are near 1 Hz. Although this argument may be true, REI

[1]Oral communication from Nelson, W.J. (November 30, 1998) and Street, R.L. (March 12, 1999) to J. Stamatakos, Center for Nuclear Waste Regulatory Analyses. Written notes of those conversations have been transmitted to the Nuclear Regulatory Commission.

PSHA results should be used with great caution for design of structures and components with higher natural frequencies and for designs based on the PGA.

— As pointed out by the REI (1999) report, the maximum magnitudes assigned to the NMSZ faults were based on Johnston (1996) estimates, which were extrapolated from the intensity observation data of the 1811–1812 events. This extrapolation leads to the largest published magnitudes (**M** 7.8 to **M** 8.11) for the 1811–1812 earthquake sequence, and does not include other opinions in the scientific community [e.g., Nuttli (1973)], where the magnitudes for the 1811–1812 events are considered to range between **M** 7.0 and **M** 7.2. Furthermore, these larger magnitudes have been questioned by some seismologists and geologists based on California experience and the tectonic setting of the NMSZ, as indicated by the REI (1999) report. Because the Johnston (1996) estimates are conservative in the sense that they lead to a higher overall hazard, the REI (1999) values are acceptable.

— The CNWRA reviewers endorse the REI (1999) suggestion to limit the application of its PSHA results to return periods of 500 yr or less. As indicated by the REI (1999) report, the evaluation of seismic hazard for longer return periods should include a broader characterization of uncertainty by considering multiple source-characterization and ground-motion experts.

5 REFERENCES

Atkinson, G.M., and D.M. Boore. 1997. Some comparisons between recent ground motion relations. *Seismological Research Letters* 68(1): 24–40.

Atkinson, G.M., and W. Silva. 1997. An empirical study of earthquake source spectra for California earthquakes. *Bulletin of the Seismological Society of America* 87: 97–113.

Bear, G.W., J.A. Rupp, and A.J. Rudman. 1997. Seismic interpretation of the deep structure of the Wabash Valley fault system. *Seismological Research Letters* 68(4): 624–640.

Boore, D.M. 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. *Bulletin of the Seismological Society of America* 73: 1,865–1,894.

Boore, D.M. 1986. Short-period P- and S-wave radiation from large earthquakes: Implications for spectral scaling relations. *Bulletin of the Seismological Society of America* 76(1): 43–64.

Braile, L.W., G.R. Keller, W.J. Hinze, and E.G. Lidiak. 1982. An ancient rift complex and its relation to contemporary seismicity in the New Madrid seismic zone. *Tectonics* 1: 225–237.

Chen, R., J.A. Stamatakos, and A.H. Chowdhury. 1998. *Final Review Plan for Probabilistic Seismic Hazard Assessment of Paducah Site.* San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Cornell, C.A. 1968. Engineering seismic risk analysis. *Bulletin of the Seismological Society of America* 58: 1,583–1,606.

Cornell, C.A. 1971. Probabilistic analysis of damage to structures under seismic loads. *Dynamic Waves in Civil Engineering*. Wiley Interscience.

Cox, R.T., and VanArsdale, R.B., 1997. Hotspot origin of the Mississippi embayment and its possible impact on contemporary seismicity. *Engineering Geology* 46(3.4): 5–12.

Dalziel, I.W. 1997. Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. *Bulletin of the Geological Society of America* 109: 16–42.

Der Kiureghian, A. 1975. *A Line Source Model for Seismic Risk Analysis.* Technical Report UILU–ENG–75–2023. Urbana, IL: University of Illinois.

Electric Power Research Institute. 1988. *Seismic Hazard Methodology for Central and Eastern United States.* EPRI NR–4726, Vols. 1–10. Palo Alto, CA: Electric Power Research Institute.

Electric Power Research Institute. 1993. *Guidelines for Determining Design Basis Ground Motions.* EPRI TR–102293, Vols. 1–4, Palo Alto, CA: Electric Power Research Institute.

Galloway, M. 1999. *Paducah Gaseous Diffusion Plant Seismic Hazard Analysis.* Letter (March 11) to J.A. Adkins. Paducah, KY: U.S. Enrichment Corporation.

Gutenberg, B., and C.F. Richter. 1954. *Seismicity of the Earth.* Princeton, NJ: Princeton University Press.

Hanks, T.C., and H. Kanamori. 1979. A moment magnitude scale. *Journal of Geophysical Research* 84: 2,348–2,350.

Hanks, T.C., and R.K. McGuire. 1981. The character of high-frequency strong ground motion. *Bulletin of the Seismological Society of America* 71: 2,071–2,095.

Hwang, H., and J.R. Huo. 1997. Attenuation relations of ground motion for rock and soil sites in eastern United States. *Soil Dynamics and Earthquake Engineering* 16: 363–372.

Johnston, A.C. 1996. Seismic moment assessment of earthquakes in stable continental regions-III: New Madrid 1811–1812, Charleston 1886 and Lisbon 1755. *Geophysical Journal International* 126: 314–344.

Johnston, A.C., K.J. Coppersmith, L.R. Kanter, and C.A. Cornell. 1993. *The Earthquakes of Stable Continental Regions*. Final Report No. TR–102261. Palo Alto, CA: Electric Power Research Institute.

Kelson, K.I., G.D. Simpson, R.B. VanArsdale, C.C. Haraden, and W.R. Lettis. 1996. Multiple late Holocene earthquakes along the Reelfoot fault, central New Madrid seismic zone. *Journal of Geophysical Research* 101(B3): 6,151–6,170.

Langenheim, V.E., and T.G. Hildenbrand. 1997. Commerce geophysical lineament—Its source, geometry, and relation to the Reelfoot rift and New Madrid seismic zone. *Bulletin of the Geological Society of America* 109(5): 580–595.

Marshak, S., and T. Paulsen. 1997. Structural style, regional distribution, and seismic implications of midcontinent fault-and-fold zones, United States. *Seismological Research Letters* 68(4): 511–520.

McGuire, R.K. 1976. *FORTRAN Computer Program for Seismic Risk Analysis*. OFR 76–67. Reston, VA: U.S. Geological Survey.

McGuire, R.K. 1978. *FRISK: Computer program for seismic risk analysis using faults as earthquake sources*. OFR 78-1007. Reston, VA: U.S. Geological Survey.

Mueller, C., M. Hopper, and A. Frankel. 1997. *Preparation of Earthquake Catalogs for the National Seismic-Hazard Maps: Contiguous 48 States*. Open-File Report 97-464. Reston, VA: U.S. Geological Survey.

Nelson, W.J., F.B. Denny, J.A. Devera, L.R. Follmer, and J.M. Masters. 1997. Tertiary and quaternary tectonic faulting in southernmost Illinois. *Engineering Geology* 46(3-4): 235–258.

Nuclear Regulatory Commission. 1973. *Design Response Spectra for Seismic Design of Nuclear Power Plants*. Regulatory Guide 1.60. Washington, DC: Nuclear Regulatory Commission, Office of Standards Development.

Nuclear Regulatory Commission. 1995. *General Site Suitability Criteria for Nuclear Power Stations*. Regulatory Guide 4.7. Washington, DC: Nuclear Regulatory Commission, Office Standards Development.

Nuclear Regulatory Commission. 1997a. *Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion.* Regulatory Guide 1.165. Washington, DC: Nuclear Regulatory Commission, Office of Standards Development.

Nuclear Regulatory Commission. 1997b. *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants.* NUREG–0800. Washington, DC: Nuclear Regulatory Commission.

Nuclear Regulatory Commission. 1998a. *Certification of Gaseous Diffusion Plants.* Code of Federal Regulations, Title 10—Energy, Chapter 1—Nuclear Regulatory Commission, Part 76. Washington, DC: U.S. Government Printing Office.

Nuclear Regulatory Commission. 1998b. *Domestic Licensing of Production and Utilization Facilities.* Code of Federal Regulations, Title 10—Energy, Chapter 1—Nuclear Regulatory Commission, Part 50 and Appendix A to Part 50. Washington, DC: U.S. Government Printing Office.

Nuclear Regulatory Commission. 1998c. *Reactor Site Criteria.* Code of Federal Regulations, Title 10—Energy, Chapter 1—Nuclear Regulatory Commission Part 100. Washington, DC: U.S. Government Printing Office.

Nuttli, O.W. 1973. The Mississippi Valley earthquakes of 1811 and 1812: intensities, ground motion, and magnitudes. *Bulletin of the Seismological Society of America* 63: 227–248.

Persinko, A. 1998. *Meeting Summary–Paducah Seismic Hazard Study with U.S. Enrichment Corporation.* Letter (June 2) to R.C. Pierson, Office of Nuclear Material Safety and Safeguards, Nuclear Regulatory Commission. Washington, DC: Nuclear Regulatory Commission.

Pierson, R.C. 1998a. *Paducah Gaseous Diffusion Plant Seismic Hazard Analysis.* Letter (May 13) to S.A. Toelle, U.S. Enrichment Corporation. Washington, DC: Nuclear Regulatory Commission.

Pierson, R.C. 1998b. *Paducah Gaseous Diffusion Plant Seismic Hazard Analysis.* Letter (October 21) to S.A. Toelle, U.S. Enrichment Corporation. Washington, DC: Nuclear Regulatory Commission.

Risk Engineering, Inc. 1993. *Seismic Hazard Evaluation for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky.* K/GDP/SAR/SUB–1. Boulder, CO: Risk Engineering, Inc.

Risk Engineering, Inc. 1998a. *Updated Probabilistic Seismic Hazard Analysis for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky.* Final Report. Revision 1. Boulder, CO: Risk Engineering, Inc.

Risk Engineering, Inc. 1998b. *Updated Probabilistic Seismic Hazard Analysis for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky.* Final Report. Revision 2. Boulder, CO: Risk Engineering, Inc.

Risk Engineering, Inc. 1999. *Updated Probabilistic Seismic Hazard Analysis for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky.* Final Report. Revision 3. Boulder, CO: Risk Engineering, Inc.

Russ, D.P. 1982. Style and significance of surface deformation in the vicinity of New Madrid, Missouri, in investigations of the New Madrid, Missouri earthquake region. F.A. McKeown and L.C. Pakiser, eds. *U.S. Geological Survey, Professional Paper* 1236: 95–114.

Schnabel, P.B., J. Lysmer, and H.G. Seed. 1972. *SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites.* EERC 72-12. Berkeley, CA: University of California at Berkeley, Earthquake Engineering Research Center.

Schwartz, D.B., and K.J. Coppersmith. 1984. Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas faults. *Journal of Geophysical Research* 89: 5,681–5,698.

Schweig, E.S., and R.B. VanArsdale. 1996. Neotectonics of the upper Mississippi embayment. *Engineering Geology* 45(1-4): 185–203.

Seeber L., and J.G. Armbruster. 1991. *The NCEER-91 Earthquake Catalog: Improved Intensity-Based Magnitudes and Recurrence Relations for U.S. Earthquakes East of New Madrid.* 91-0021. Buffalo, NY: State University of New York, National Center for Earthquake and Engineering Research.

Seed, H.B., and I.M. Idriss. 1970. *Soil Moduli and Damping Factors for Dynamic Response Analyses.* UCB/EERC–70/10. Berkeley, CA: University of California at Berkeley, Earthquake Engineering Research Center.

Senior Seismic Hazard Analysis Committee. 1997. *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts.* NUREG/CR–6372. Washington, DC: Nuclear Regulatory Commission.

Silva, W.J. 1976. Body waves in a layered anelastic solid. *Bulletin of the Seismological Society of America* 66(5): 1,539–1,554.

Silva, W.J. 1991. Global characteristics and site geometry. *Proceedings of the NSF EPRI Workshop on Dynamic Soil Properties and Site Characterization.* EPRI NP–7337. Palo Alto, CA: Electric Power Research Institute.

Silva, W.J. 1997. Characteristics of vertical strong ground motions for applications to engineering design. *Proceedings of the FHWA/NCEER Workshop on the National Representation of Seismic Ground Motions for New and Existing Highway Facilities.* NCEER–97–0010. Buffalo, NY: National Center for Earthquake Engineering Research.

Staub, W.P., and J.C. Wang. 1991. Analysis of bore-hole seismic velocity surveys at the Paducah Gaseous Diffusion Plant. *Third DOE Natural Phenomena Hazards Mitigation Conference, St Louis, Missouri, October 15–18, 1991.* Washington, DC: U.S. Department of Energy.

Toelle, S.A. 1997. *Compliance Plan Issue 36–Transmittal of Updated Seismic Risk Analysis for NRC Approval (GDP 97-0201).* Letter (December 1) to R.C. Pierson, Office of Nuclear Material Safety and Safeguards, Nuclear Regulatory Commission. Paducah, KY: U.S. Enrichment Corporation.

Toelle, S.A. 1998. *Paducah Gaseous Diffusion Plant Compliance Plan Issue 36. Response to NRC Request for Additional Information. Updated Seismic Hazard Analysis (TAC No. L32054).* Letter (March 6) to C.J. Paperiello, Office of the Director, Office of Nuclear Material Safety and Safeguards, Nuclear Regulatory Commission. Paducah, KY: U.S. Enrichment Corporation.

Toro, G.R., N.A. Abrahamson, and J.F. Schneider. 1997. Model of strong ground motions from earthquakes in Central and Eastern North America: Best estimates and uncertainties. *Seismological Research Letters* 68(1): 41–57.

U.S. Department of Energy. 1994a. *Guidelines for Use of Probabilistic Seismic Hazard Curves at Department of Energy Sites*. DOE–STD–1024. Washington, DC: U.S. Department of Energy.

U.S. Department of Energy. 1994b. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*. DOE–STD–1020. Washington, DC: U.S. Department of Energy.

VanArsdale, R.B. 1997. Hazard in the heartland: The New Madrid seismic zone. *Geotimes* 42(5): 16–19.

Vanmarcke, E. 1976. Structural response to earthquakes. *Seismic Risk and Engineering Decisions*. C. Lomnitz and E. Rosenblueth, eds., Amsterdam, Lodon, New York: Elsevier Publishing Co. Chapter 8.

Weber, J., S. Stein., and J. Engeln. 1998. Estimation of interplate strain accumulation in the New Madrid seismic zone from repeat seismic surveys. *Tectonics* 17: 250–266.

Wells, D.L., and K.J. Coppersmith. 1994. New empirical relationships among magnitude, rupture length, rupture area, and surface displacement. *Bulletin of the Seismological Society of America* 84: 974–1,002.

Zoback, M.L., and 36 project participants. 1992. World stress map maximum horizontal stress orientations. *Journal of Geophysical Research* 97: 11,703–11,728.

6 GLOSSARY

Capable Fault[1] — A fault defined by the Nuclear Regulatory Commission as one that is "capable" of "near future" movement; in general, a fault on which there has been movement within the last 35,000 yr, or repeated movement in the last 500,000 yr. See appendix A of 10 CFR Part 100.

Characteristic Earthquake Recurrence Model[2] — Model for predicting the distribution of earthquake magnitudes on a fault in which the maximum magnitude earthquake occurs repeatedly and more frequently than one would predict from a simple exponential or Gutenberg and Richter recurrence relationship.

Clustered Activity[2] — A series of earthquakes on a fault or fault system over a period of time significantly shorter than the recurrence rate of the fault.

Contemporary Stress Field — Present conditions of stress in the Earths crust at a given local.

Epicenter Focus Depth[1] — The depth from the point on the Earth's surface to the focus of the earthquake or the point on the fault within the Earth where the earthquake nucleated.

Exponential Earthquake Recurrence Model[2] — Model for predicting the distribution of earthquake magnitudes in which the number of earthquakes of different magnitudes varies systematically following the equation: $M=a\text{-}bN$, where M is the magnitude, N is the number of events, and a and b are constants. The exponential recurrence model is also known as the Gutenberg and Richter recurrence model.

Holocene[1] — The subdivision of geologic time spanning approximately the last 10,000 yr.

Iapetan Rift[1] — Ancient system of extensional faults and related basins along the eastern margin of North America that developed in the Precambrian (prior to about 750 million years ago) during the opening of an ocean basin referred to as the Iapetus Ocean.

Mesozoic[1] — The subdivision of geologic time from about 245 to about 65 million years ago.

Microseismicity — Earthquakes recorded by seismographs that are too small in magnitude to be felt at the Earth's surface.

GLOSSARY (cont'd)

Modified Mercalli Intensity Scale[1] A relative intensity scale of earthquake size based on the resulting damage developed in 1931 by the American seismologists Harry Wood and Frank Neumann. The intensity scale consists 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction and, is designated by Roman numerals.

Moment Magnitude (M_W)[1] A measurement of Earthquake size calculated from the seismic moment of the earthquake.

Neoproterozoic The subdivision of geologic time of the Proterozoic from about 1,000 and 570 million years ago.

Normal Fault A fault with a dip of 45 degrees or greater over much of its extent, on which the hangingwall appears to have moved downward relative to the footwall. Normal faults are the product of extensional strains.

Paleozoic[1] The subdivision of geologic time that extends from time from about 570 to about 245 million years ago.

Pannotia[3] A supercontinent that may have existed in the latest Neoproterozoic time after the opening of the Pacific Ocean basin.

Phanerozoic The subdivision of geologic time spanning the last 570 million years.

Pliocene[1] The subdivision of geologic time from about 5.3 to about 2.0 million years ago.

Quaternary[1] The subdivision of geologic spanning the last 2 million years.

Restraining Bend[1] A bend in a strike-slip fault where fault movement results in the development of localized contractional strain.

Reverse Fault A fault with a dip of 45 degrees or greater over much of its extent, on which the hangingwall appears to have moved upward relative to the footwall. Normal faults are the product of contractional strains.

Seismic Moment[1] A measure of the strength of an earthquake, particularly of the low-frequency wave motion. The seismic moment is equal to the product of the force and the moment arm of the double-couple system of forces that produces ground displacements equivalent to that produced by the actual earthquake dislocation. The seismic moment also is equal to the product of the rigidity modulus of the Earth material, the fault area, and the average dislocation along the fault surface.

GLOSSARY (cont'd)

Strike-Slip Fault — A fault on which the fault blocks move horizontally past one another. There are two types, right-lateral strike slip faults in which the fault block opposite to the observer has been displaced to the right and left-lateral strike-slip fault in which the fault block opposite to the observer has been displaced to the left.

Thrust Fault — A fault with a dip of 45 degrees or less over much of its extent, on which the hangingwall appears to have moved upward relative to the footwall. Horizontal compression rather than vertical displacement is its characteristic feature.

Transpression[1] — Crustal deformational movement representing an intermediate stage between compressional and strike-slip motion; it occurs in zones with oblique compression and combines strike-slip or wrench movement with a superposed compression perpendicular to the wrench or strike-slip zone.

[1] Glossary of Geology, Fourth Edition. 1997. J.A. Jackson, ed. American Geologic Institute, Alexandria, VA.
[2] Yeats, R.S., K. Sieh, and C.R. Allen. 1997. *The Geology of Earthquakes*. NY: Oxford University Press.
[3] Dalziel, I.W.D. 1997. Neoproterozoic-paleozoic geography and tectonics: Review, hypothesis, environmental speculation, *Geological Society of America Bulletin* 109: 16–42.

January 21, 2000

J. Adkins

If you have any questions regarding this action, contact Charlie Cox of my staff at (301) 415-6755. Please reference the above TAC No. in future correspondence related to this request.

Sincerely,

Original signed by

Melanie A. Galloway, Chief
Enrichment Section
Division of Fuel Cycle Safety
and Safeguards, NMSS

Docket 70-7001
Certificate GDP-1

Enclosures: 1. Compliance Evaluation Report
2. CNWRA Final Report

cc: Mr. Howard Pulley, Paducah
Mr. Steven A. Toelle, USEC-Headquarters
Mr. Randall DeVault, DOE-Oak Ridge

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